JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 87, NO. B6, PAGES 4697-4714, JUNE 10, 1982

UNCERTAINTIES IN THE RELATIVE POSITIONS OF THE AUSTRALIA, ANTARCTICA, LORD HOWE, AND PACIFIC PLATES SINCE THE LATE CRETACEOUS

Joann Stock and Peter Molnar

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Abstract. We determined parameters that describe finite rotations and their uncertainty regions for relative plate motion at the spreading centers between the Pacific and Antarctica plates, between Australia and Antarctica, and between the Lord Howe Rise and Australia. We combined these to yield a range of possible finite rotations describing the relative positions of the Pacific, Australia, Antarctica, and Lord Howe plates since the Late Cretaceous. If the Pacific-Australia plate boundary has had its present trend since anomaly 18 time, reconstructions show 330 ± 110 km of motion of the Pacific plate relative to the Lord Howe Rise since anomaly 5 time (9.8 m.y.), 420 ± 110 km since anomaly 6 time (19.5 m.y.), 770 ± 330 km since anomaly 13 time (35.6 m.y.), and 820 ± 260 km since anomaly 18 time (43.0 m.y.). We examined two cases for times prior to anomaly 18, assuming a Late Cretaceous age of Australia-Antarctica separation. If a plate boundary existed between the Lord Howe Rise and Pacific plates since the Late Cretaceous, with no plate boundary in Antarctica, reconstructions with the Lord Howe Rise fixed predict 610 ± 200 km of westward motion of the Pacific plate between the times of anomalies 31 and 22, followed by 260 ± 100 km of northward motion between the times of anomalies 22 and 18. If the Lord Howe Rise was fixed to the Pacific plate until the Eocene, but a plate boundary existed between East and West Antarctica, reconstructions show very little motion across this boundary between the times of anomalies 31 and 22, followed by convergence between the times of anomalies 22 and 18. This second case also brings 70-80 m.y. paleomagnetic poles from the Pacific and East Antarctica plates into better agreement than the first case, but large uncertainties in the reconstructions do not allow the first case to be conclusively eliminated.

Introduction

Reconstructions of the past relative positions of lithospheric plates, derived from matching magnetic anomaly and fracture zone data across spreading centers, provide important constraints on the amount of displacement between rigid plates separated by convergent or transform boundaries. In the South Pacific and southeast Indian Ocean, reconstructions of Pacific-Antarctica and Antarctica-Australia relative positions can be used to study the evolution of the Pacific-Australia plate boundary through New Zealand since the Late Cretaceous [e.g. Molnar et al., 1975; Weissel et al., 1977]. Most reconstructions have been made without detailed analysis of their uncertainties, however, so the range of possible relative positions between these plates at a given time has not been discussed (see Walcott [1978] for an exception). Here we examine the uncertainties in these reconstructions and combine them to study two problems: the range of possible motion along the Pacific-Australia boundary during the latter half of the Cenozoic, and the possible existence of other plate boundaries in this system since Late Cretaceous time.

A reconstruction of the relative positions of two converging plates cannot be directly obtained; instead, it is found by matching magnetic anomalies and fracture zones across other spreading centers that separate the two converging plates from other plates. To determine the uncertainties in such a reconstruction, one must obtain the range of possible poles and angles for each pair of plates and then combine them to estimate the resultant range of possible poles and angles for the two converging plates. We recomputed finite rotations for the Pacific-Antarctica and Antarctica-Australia spreading centers, incorporating estimates of uncertainties in the locations of the data points to determine the range of possible poles and angles which yield acceptable fits for a given reconstruction. These possible reconstructions were then combined to obtain a range of possible plate reconstructions in the South Pacific-southeast Indian Ocean-Tasman Sea area for Late Cretaceous and Cenozoic time. This study is part of a larger project in which we will combine these results with poles and uncertainty regions from other oceans to obtain uncertainties in the past relative positions of Pacific-North America, Farallon-North America and Nazca-South America plates.

Method for Determining Poles and Angles

All of the data used here were reevaluated from published magnetic and bathymetric profiles or from ship crossings of fracture zones on published maps. We reexamined the positions of magnetic anomaly points to eliminate dubious identifications and to insure that in each anomaly the locations for each correspond to the same age in the reversal history. We also reevaluated all of the fracture zone positions and kept only those data points that are on ship tracks and have either definite bathymetric expressions or for which an offset can be reasonably inferred from missing or repeated magnetic anomalies. Based on the accuracy of navigation and the quality of magnetic and bathymetric data, we assigned an estimate of uncertainty (in kilometers) to the position of each data point (see Appendix A on

Copyright 1982 by the American Geophysical Union.

Paper number 1B1871.
0148-0227/82/001B-1871$05.00

TABLE 1. Best Fit Poles and Angles and Poles and Angles Representing the Outer Limits of Maximum Possible Uncertainty Regions for Revised Reconstructions

Region	Best Pole	Four End-Members			
		1	2	3	4
South Pacific					
Pacific-Antarctica					
A5	72.0°N,	69.0°N,	75.0°N,	73.0°N,	71.0°N,
	70.0°W	80.0°W	60.0°W	76.0°W	68.0°W
	9.75	9.10°	10.40°	9.75°	9.70°
A6	71.25°N,	73.0°N,	69.0°N,	71.0°N,	71.0°N,
	73.19°W	68.0°W	78.0 W	76.0°W	71.0°W
	15.41°	15.95°	14.80°	15.25°	15.45°
A13	74.83°N,	74.20°N,	75.40°N,	77.30°N,	70.60°N,
	56.86°W	57.0°W	57.0°W	34.0°W	73.0°W
	28.01°	27.85°	28.14°	32.62°	24.71°
A18	75.08°N,	74.70°N,	75.40°N,	75.90°N,	74.30°N,
	51.25°W	51.25°W	51.25°W	44.0°W	57.0°W
	32.56°	32.62°	32.48°	34.23°	31.17°
A25	71.61°N,	72.0°N,	71.0°N,	74.0°N,	70.0°N,
	57.47°W	60.0°W	56.0°W	44.0°W	62.0°W
	40.11°	39.65°	40.40°	44.60°	38.35°
A31	71.65°N,	72.0°N,	70.0°N,	72.0°N,	71.0°N,
	41.0°W	40.0°W	56.0°W	50.0°W	48.0°W
	53.75°	57.25°	50.45°	53.70°	53.60°
Southeast Indian Ocean					
Australia-Antarctica					
A5	8.70°N,	4.0°N,	13.0°N,	7.0°N,	11.0°N,
	35.56°E	34.0°E	36.0°E	31.0°E	40.0°E
	-6.65°	-6.60°	-6.70°	-6.65°	-6.65°
A6	8.95°N,	18.0°N,	5.0°N,	7.0°N,	11.0°N,
	12.07°E	29.0°E	34.0°E	30.0°E	34.0°E
	-11.90°	-12.10°	-11.80°	-11.92°	-11.86°
A13	11.68°N,	14.0°N,	8.0°N,	13.0°N,	10.0°N,
	31.81°E	30.0°E	35.0°E	33.0°E	31.0°E
	-20.46°	-20.74°	-20.08°	-20.56°	-20.42°
A18	11.47°N,	14.0°N,	7.0°N,	13.0°N,	9.0°N,
	31.03°E	32.0°E	33.0°E	37.0°E	28.0°E
	-23.58°	-23.70°	-22.86°	-23.32°	-23.44°
Tasman Sea					
Lord Howe-Australia					
A28	4.49°S,	12.0°S,	8.0°N,	4.0°S,	4.0°S,
	139.36°E	140.0°E	138.0°E	136.0°E	144.0°E
	-5.66°	-6.72°	-4.64°	-5.48°	-5.80°
A32	10.63°S,	18.0°S,	0.0,	13.0°S,	8.0°S,
	139.33°E	144.0°E	132.0°E	137.0°E	142.0°E
	-12.30°	-16.48°	-9.26°	-13.01°	-11.82°

microfiche)[1]. The numbers and ages of the magnetic anomalies used in these reconstructions are based on the time scale of LaBrecque et al. [1977]: anomaly 5 (9.8 m.y.), anomaly 6 (19.5 m.y.), anomaly 13 (35.6 m.y.), anomaly 18 (43.0 m.y.), anomaly 25 (59.0 m.y.), anomaly 28 (64.0 m.y.), anomaly 31 (67.8 m.y.), and anomaly 32 (71.9 m.y.).

Each new pole and angle was computed using Hellinger's [1979] method. This method consists of two steps: a search to find the angle of rotation about a given pole that gives the best fit to the data and an iterative search within a specific region to find the location of the pole that gives the best fit. The data were divided into separate groups for each continuous magnetic anomaly or fracture zone segment; points on one

[1]Appendices are available with entire article on microfiche. Order from American Geophysical Union, 2000 Florida Avenue, N.W., Washington, D.C. 20009. Document J82-01; $1.00. Payment must accompany order.

plate were rotated to the other plate about a pole, and a separate great circle was fit to the data for each segment. The distance of each data point on the segment from its great circle was then computed and divided by the uncertainty in position assigned to that point to provide a weighted distance for the point. The sum of the squares of all the weighted distances (a measure of fit) was minimized to obtain the best fit angle of rotation for the particular pole position. A search was then conducted to find the pole position with the smallest measure of fit.

The method described above gave an estimate of the pole and angle that yielded the best fitting rotation for the two plates. We were also interested in determining the uncertainty in each best fit pole and angle. This uncertainty is represented by a region in latitude-longitude space containing poles with different angles that yield possible fits to the data used, given the uncertainties in the data. This uncertainty region was obtained by mapping the measure of fit as a function of the pole position on a grid of latitude and longitude lines in the region surrounding the best pole. For a pole at each latitude-longitude point on the grid, we found the angle with the smallest measure of fit. Pole positions with equal measures of fit were then contoured to give an estimate of the shape of the uncertainty region in latitude and longitude. To find the extent of the uncertainty region, reconstructions were made using poles and angles along the axes of the measure-of-fit contour regions. We examined each of these reconstructions carefully to determine whether it provided an acceptable fit to the data within the previously estimated uncertainties in the data points. This uncertainty region is therefore subjective in that its boundary represents poles that in our opinion, constitute marginal or unacceptable matches of the data. Often this boundary region follows a constant measure-of-fit contour, but this is not always so. We define this region by the position of the best fitting pole and the corresponding angle, with four other pole positions and corresponding angles for those poles that mark the ends and sides of the elliptical confidence region surrounding the best fitting pole (Table 1). End-member fits and uncertainty regions for one time period from each ocean are shown in the text (Figures 2, 6, and 13); end-member fits for additional anomalies in each ocean are shown in microfiche Appendix B.

Discussion of Reconstructions

Southeast Indian Ocean

Fracture zone control in the southeast Indian Ocean is poor. The complicated topography associated with most of the southeast Indian Ocean, especially in the Australia-Antarctica discordant zone and in the vicinity of the ridge axis, makes it difficult to identify fracture zones, although general trends have been inferred by previous workers [Weissel and Hayes, 1972; Weissel et al., 1977].

We reevaluated all of the unpublished USNS Eltanin magnetic and bathymetric data available for fracture zone crossings in this region and we examined identifications of magnetic anomalies in Schlich [1975] and Sclater et al. [1976] (Appendix A). Although there are many places where the Eltanin tracks cross fracture zones, these fracture zone points are uniformly distributed throughout the region. They do not show a pattern of widely spaced individual fracture zones with substantial offset, as in the South Pacific; rather, they indicate many closely spaced fracture zones with small offsets of the magnetic lineations on either side. Because of the wide spacing of the Eltanin tracks compared to the inferred spacing of the fracture zones, individual fracture zones cannot be correlated to the north or south. In addition, the many small offsets of the current ridge axis make it difficult to correlate fracture zones across the Australia-Antarctica plate boundary.

Rather than base our reconstructions on inferred fracture zone trends, we have used the only fracture zones that we can confidently identify as continuous features: the Tasman and Balleny fracture zones on the Antarctica plate, north and west of the Balleny Islands [Hayes and Connolly, 1972].

The spacing between the Tasman and Balleny fracture zones is approximately equal to the width of the southwestern margin of the South Tasman Rise, and the offset of isobaths on the Balleny fracture zone is about equal to the offset of the two halves of the southern margin of the South Tasman Rise. Therefore, we correlate the Tasman fracture zone on the Antarctica plate with the western edge of the South Tasman Rise on the Australia plate. Although we use only this one fracture zone, which can be correlated across the current spreading center, it is sufficient to constrain the fit because the magnetic anomaly points used in the reconstructions come from a ridge 7000 km long and give very strong constraints on the location of the finite poles.

The oldest recognizable magnetic anomaly due to Australia-Antarctica spreading is anomaly 34, found adjacent to the magnetic quiet zones off the Australian and Antarctic coasts [Cande and

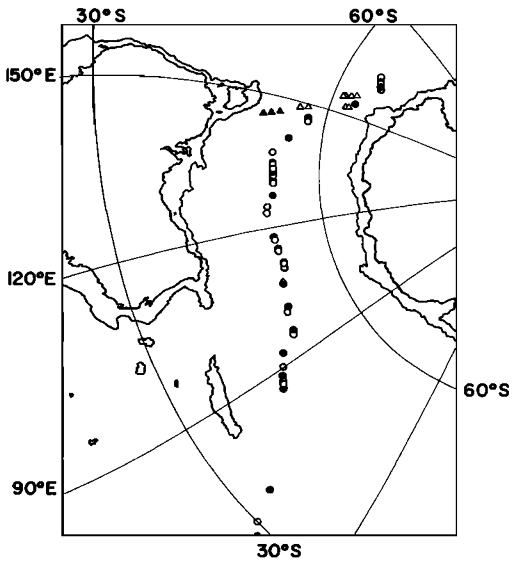

Fig. 1. Best fit reconstruction for anomaly 5, southeast Indian Ocean. Triangles, fracture zone points; circles, magnetic anomaly locations. Antarctica plate (open symbols) is held fixed and the Australia plate (solid symbols) is rotated about pole listed in Table 1.

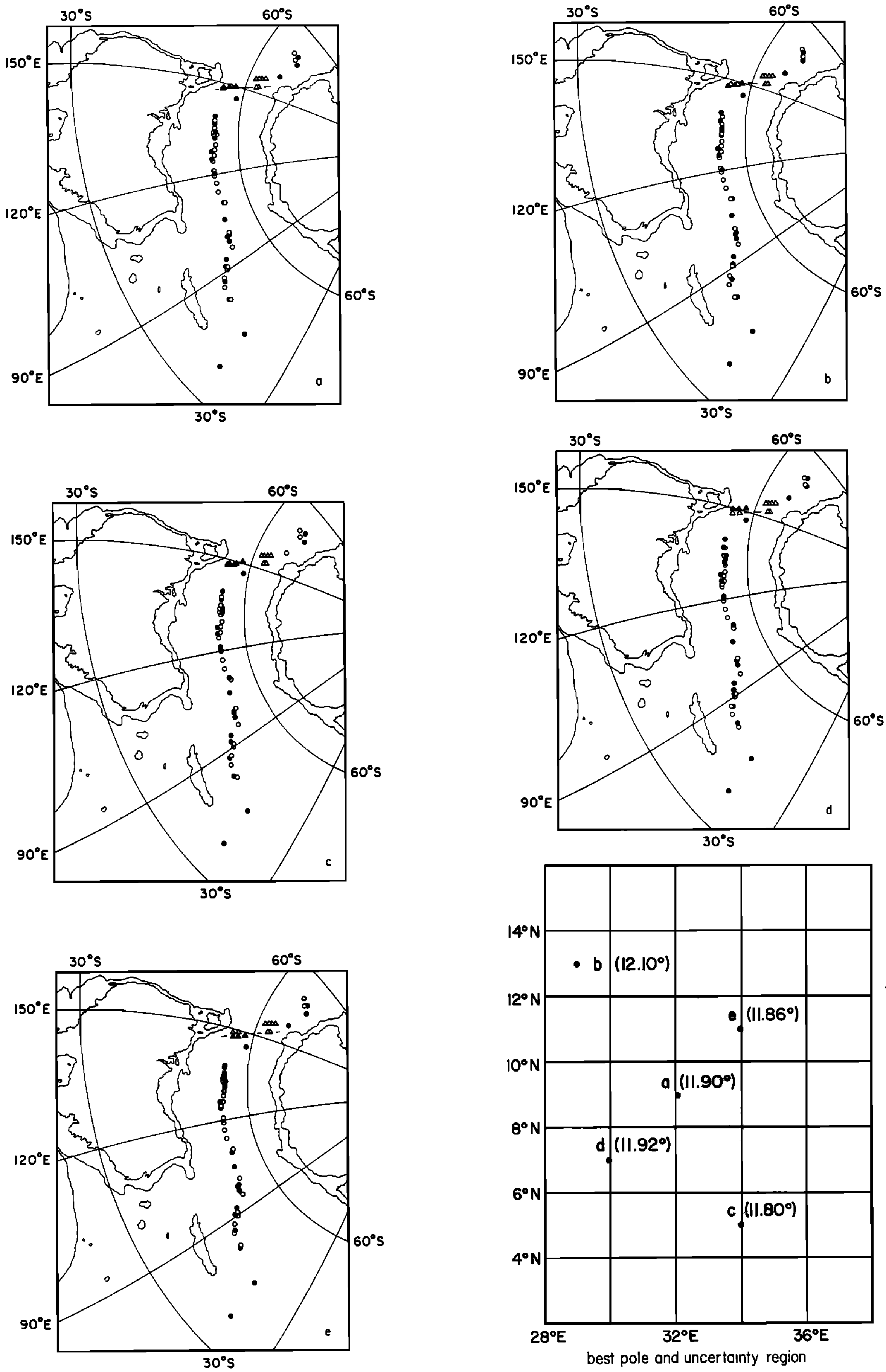

Fig. 2. Reconstructions for anomaly 6, southeast Indian Ocean. (a) Best fit rotation. (b)-(e) End-member rotations. Map showing the extent of uncertainty. Symbols are the same as in Figure 1.

Mutter, 1982]. However, until the time of anomaly 19 (44 m.y.), spreading took place very slowly, so that individual anomalies are not well resolved on marine magnetic records and are difficult to identify confidently. Anomalies younger than 18, which formed at a faster rate, are more easily identified. Rather than compute poles for these older anomalies based on uncertain data, we present reconstructions only for the times of anomalies 5, 6, 13, and 18 (Figures 1-4) for which we could recheck the magnetic anomalies.

In making reconstructions for this spreading center, one must consider the implications of possible recent deformation within the Australia plate. Seismic activity indicates that some internal deformation of the Indo-Australia plate is presently occurring southeast of India [Stein and Okal, 1978]. Seismic reflection and piston coring on both sides of the 90°E ridge show a zone of deformed sediments and basement-involved high-angle faulting, several hundred kilometers wide, that began in the late Miocene [Weissel et al., 1980]. Moreover, Minster and Jordan [1978] were not able to determine a consistent set of velocity vectors for the spreading centers in the Indian Ocean using only three plates (Africa, Antarctica, and India-Australia). They resolved this by deleting data along the India-Antarctica plate boundary between 90°E and 130°E and dividing the India plate into two plates, West India and Australia, with relative motion of slow compression in an east-west direction (1 cm/yr at 15°N, 90°E). Since the magnetic anomaly points used in our reconstructions of Australia-Antarctica spreading come from the entire length of the plate boundary (between 65°E and 175°E on the Antarctica plate and between 74°E and 160°E on the Australia plate), substantial internal deformation of the Australia plate may have affected the relative positions of anomalies on the Australia plate and could cause difficulties in computing the finite poles.

When we recomputed the finite rotations for anomalies 5, 6, and 13, we found that all the data along the length of the Australia-Antarctica plate boundary could be fit to a single pole for each time. There was no obvious misfit of data points to suggest that deformation of the Australia plate had occurred. However, the scarcity of data points west of the 90°E ridge means that our poles are strongly biased by data from what would be the Australia side of a divided Indo-Australia plate, and it is possible that with more data points from the west, a misfit would become apparent. To test this, we took Minster and Jordan's [1978] two hypothetical rotation vectors of West India-Australia convergence, to see what misfit might be expected in anomaly 5 data points near the Indian Ocean triple junction.

If assumed constant for the past 10 m.y., these two hypothetical rotation vectors displace points on the West India plate approximately 70 and 100 km parallel to the plate boundary, respectively. Although this displacement is larger than the 20 km uncertainty values associated with the points themselves, the direction of displacement is roughly parallel to the magnetic anomaly lineations and does not affect the fit obtained. Such displacement could be detected with very good fracture zone control but not with the currently available magnetic anomaly and fracture zone data.

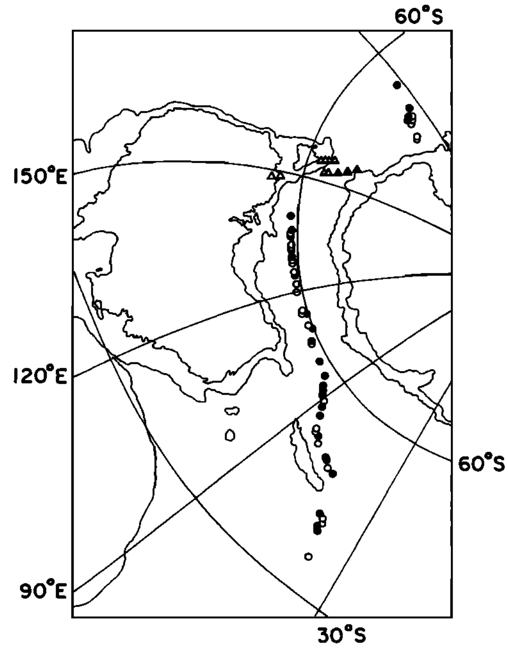

Fig. 3. Best fit reconstruction for anomaly 13, southeast Indian Ocean. Symbols are the same as in Figure 1.

In any case, our finite rotations should be valid to describe Australia-Antarctica relative positions, since they fit all of the Australia-Antarctica data acceptably.

For purposes of making reconstructions, we divided the magnetic anomaly data into three sections: points west of Kerguelen or Broken Ridge (western section); points from east of Kerguelen or Broken Ridge to south of Tasmania (central section); and points in the south Tasman Sea on the Indian plate, or east of Balleny Island on the Antarctica plate (eastern section). Best fit reconstructions for anomalies 5, 6, and 13 (Figures 1-3) show an adequate match of all three sections by rotation of the points on the Australia plate about an appropriate finite pole. However, for anomaly 18 (Figure 4) the three sections of data cannot be fit to a single plate boundary. Either the western and central sections or the eastern and central sections can be well fit to a single plate boundary, with the remaining section falling short by about 100 km or the eastern and western sections can be fit to one another, resulting in an overlap of 50-100 km in the central section. This misfit implies some deformation of either the India-Australia plate or the Antarctica plate between anomaly 18 time and anomaly 13 time. If such deformation did continue after anomaly 13 time, it was on a small enough scale that its effect is not detectable within the uncertainties in the data for anomalies 13 and 6. Therefore, we have only worried about this possible deformation for the anomaly 18 reconstruction.

There are several possible places where deformation might have occurred. The sense of the misfit is consistent with some right-lateral motion between the western and eastern parts of the Australia plate along a north-south boundary, perhaps the 90°E ridge. If such motion took place between anomaly 18 and 13 time, then the far western points should be ignored, and the best fit for

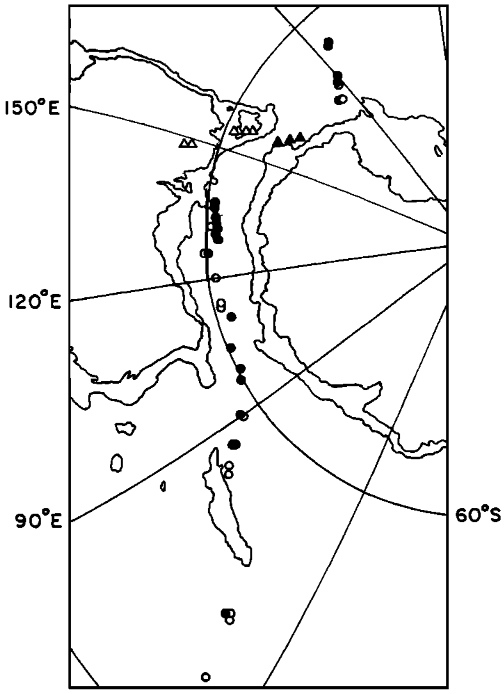

Fig. 4a

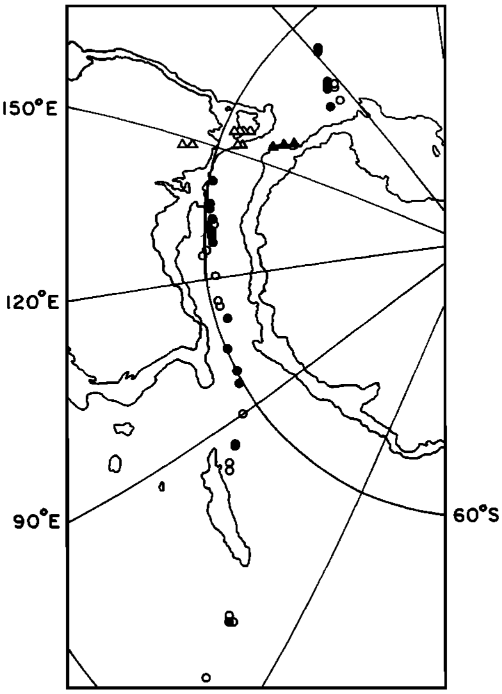

Fig. 4b

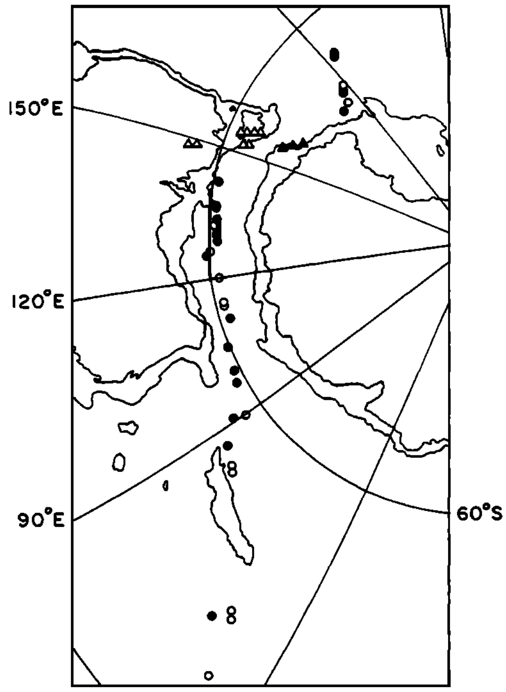

Fig. 4c

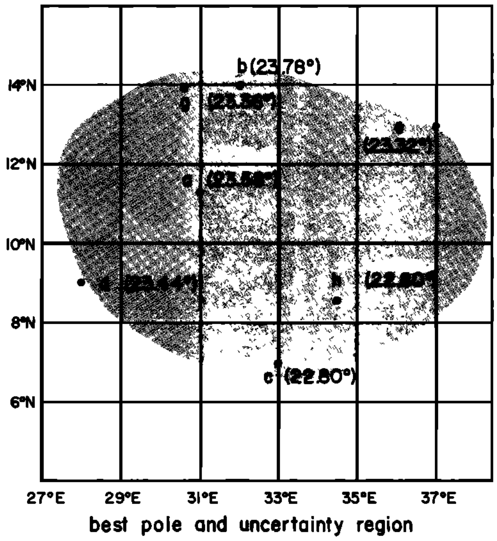

Fig. 4d

Fig. 4. Best fit reconstruction for anomaly 18, southeast Indian Ocean. (a) Best using all data. (b) Best with data east of Antarctica excluded. (c) Best with data west of 90°E excluded. (d) Locations of poles. Symbols are the same as in Figure 1.

anomaly 18 should be based only on the eastern and central sections. If the India-Australia plate has behaved rigidly but complicated ridge jumping occurred in the region of the Pacific-Antarctica-Australia triple junction, then the easternmost data points should be ignored and the fit should be based on the central and western sections. If the Antarctica plate deformed between the times of anomalies 13 and 18, then only those points on the East Antarctica half of the Antarctica plate should be used in the reconstruction.

Since not enough data exist to eliminate any of these possibilities, poles corresponding to fits based on each of these possibilities are included in the uncertainty region of the anomaly 18 pole (Figures 4 and 5). Because of this additional ambiguity, the uncertainty region for anomaly 18 in the southeast Indian Ocean is larger than the uncertainty regions for anomalies 13, 6, or 5. The pole that we use as the best fit for anomaly

18 time (Figure 4a) gives the best fit of points from all three sections, with overlap of points from the central section, and the eastern and western points falling short.

The large amount of overlap in the uncertainty regions for the poles for the times of anomalies 5, 6, 13, and 18 (Figure 5) suggests that the spreading history between Australia and Antarctica may have been relatively simple since the time of anomaly 18. Prior to anomaly 18 time, the much slower spreading rate makes it difficult to know whether Antarctica-Australia motion was occurring about a pole in the same region. The Antarctica-Australia fit for 85 m.y. based on matching the edges of the magnetic quiet zones [König, 1980] falls outside these uncertainty regions, suggesting that some change in the position of the pole took place between 85 m.y. and anomaly 18 time (43.0 m.y.).

South Pacific

Poles and uncertainty regions for Pacific-Antarctica spreading were calculated for the times of anomalies 5, 6, 13, 18, 25, and 31 (Figures 6-11). The magnetic anomaly and fracture zone locations used [from Molnar et al., 1975] come from regions both north and south of the Eltanin fracture zone system except for anomalies 25 and 31, for which there were no data points north of the Eltanin system (Appendix A).

With the exception of the pole for anomaly 5, all of the recalculated poles were close to those obtained by Molnar et al. [1975]. Molnar et al. used the instantaneous Pacific-Antarctica pole of Minster et al. [1974] for anomaly 5 time. This pole and the instantaneous poles of Minster and Jordan [1978] (RM2 geohedron and best fitting angular velocity), however, all lie outside of the recalculated uncertainty region for anomaly 5, indicating a change in the Pacific-Antarctica pole between the times of anomalies 5 and 2' or 3.

Because there are only five ship crossings of anomaly 25 on the Antarctic plate, Molnar et al. [1975] assumed symmetric spreading between the Campbell Plateau and Antarctica in order to constrain the anomaly 25 reconstruction. In our revised reconstruction, no assumption of symmetric spreading was included in the initial pole search, but the resultant pole for anomaly 25 time is nevertheless consistent with symmetric spreading (Figure 10). Since the best fit reconstructions for all the other anomalies also suggest symmetric spreading, it seems likely that the asymmetric spreading between the Campbell Plateau and Antarctica proposed by Barron and Harrison [1979] did not occur.

Paleomagnetic data from seamounts and DSDP cores in the North Pacific and the Chatham Islands on the southern part of the Pacific plate indicate that there may have been some differential movement of the northern and southern parts of the Pacific plate since the Cretaceous [Gordon and Cox, 1980; Suárez and Molnar, 1980]. In our reconstructions of Pacific-Antarctic spreading, we were able to fit all the data for each time to a single pole within the uncertainty limits. This suggests that any obvious boundary between the northern and southern portions of the Pacific plate should lie

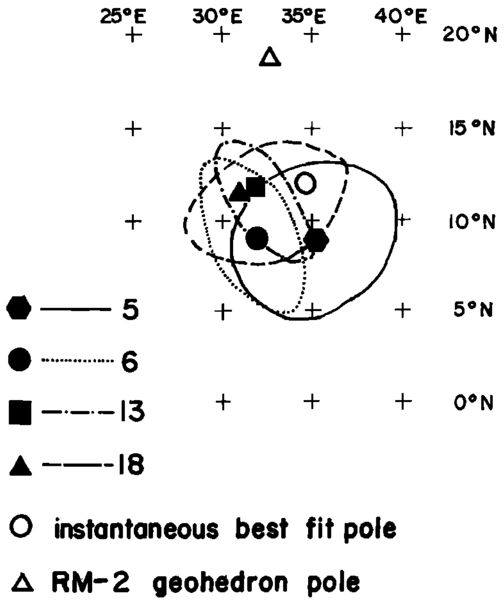

Fig. 5. Mercator projection showing the location of best fit poles and their uncertainty regions for Australia-Antarctica relative positions for the times of anomalies 5, 6, 13, and 18. Estimates of the Antarctica-India instantaneous pole from the best fitting angular velocity vector between the two plates (open circle) and RM2 geohedron (open triangle) [Minster and Jordan, 1978] are also shown.

outside the region of the data used in the reconstructions. If North Pacific-South Pacific relative motion did take place across a boundary within the region we studied, this motion was small enough that the poles are not noticeably affected.

The uncertainties in the revised reconstructions are larger than the uncertainties estimated by Molnar et al. [1975], as Hellinger [1979] found for anomalies 13 and 18. Despite these larger uncertainty regions, the general trend suggests that the pole of Pacific-Antarctica motion has been changing steadily through time. Its projection in the southern hemisphere moved south between anomaly 31 (68 m.y.) and anomaly 13 (35.6 m.y.), and then northwest between anomaly 13 and the present (Figure 12).

Tasman Sea

Magnetic anomaly locations in the Tasman Sea were reevaluated from magnetic profiles plotted perpendicular to ship track [Weissel et al., 1977; Weissel and Hayes, 1977] and from the preliminary reports of the Eltanin cruises [Hayes et al., 1975, 1976, 1977, 1978]. Fracture zone locations were reevaluated from these data sources and from Hayes and Conolly [1972]. Although many fracture zones can be inferred to exist from magnetic anomaly offsets, there are only three which have enough ship crossings to be used in the reconstruction calculations. Of these, the northernmost one cannot be shown to involve crust older than anomaly 29, so it was not used in the anomaly 32 reconstruction (Appendix A).

Northeast-southwest spreading in the Tasman Sea

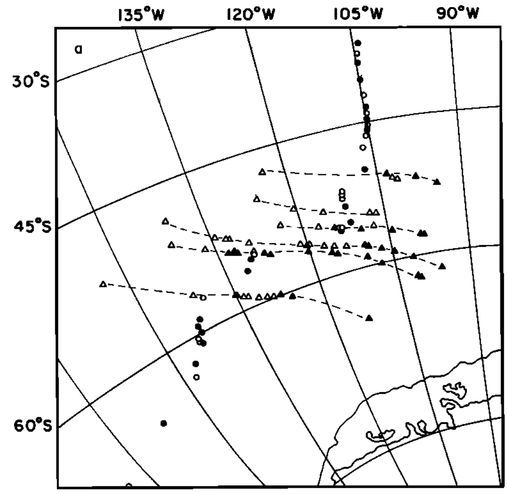

Fig. 6a

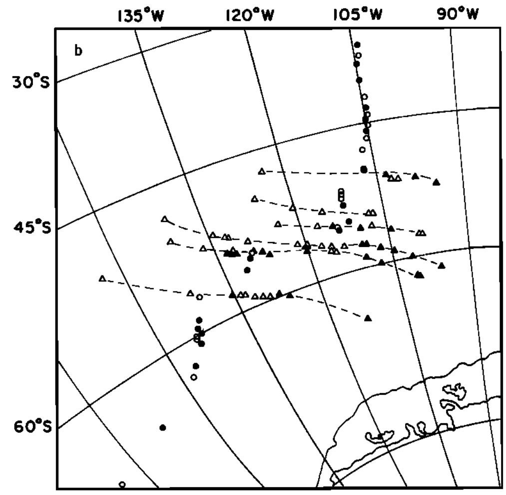

Fig. 6b

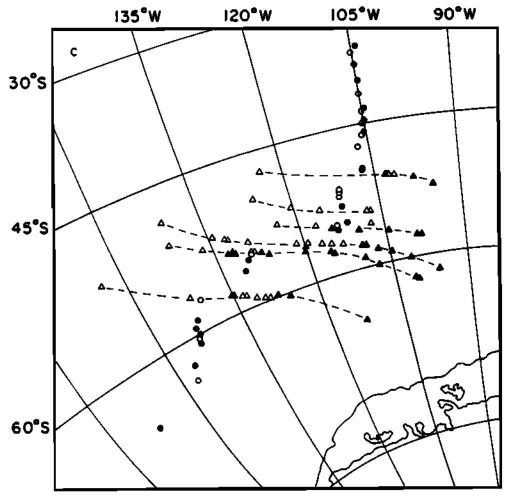

Fig. 6c

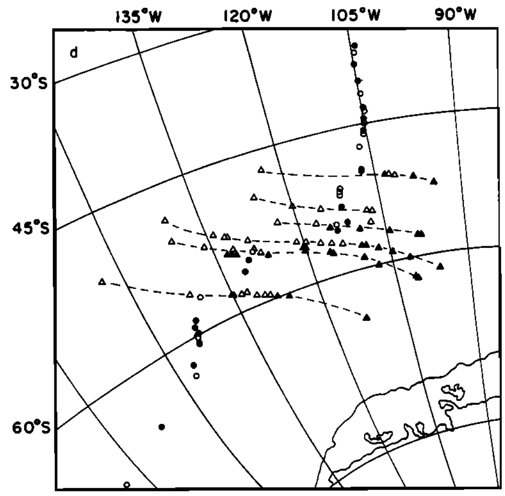

Fig. 6d

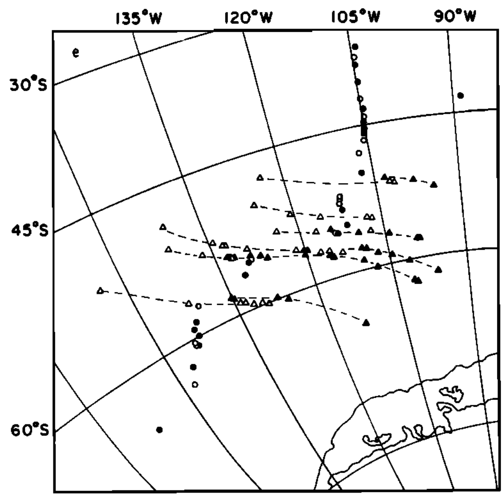

Fig. 6e

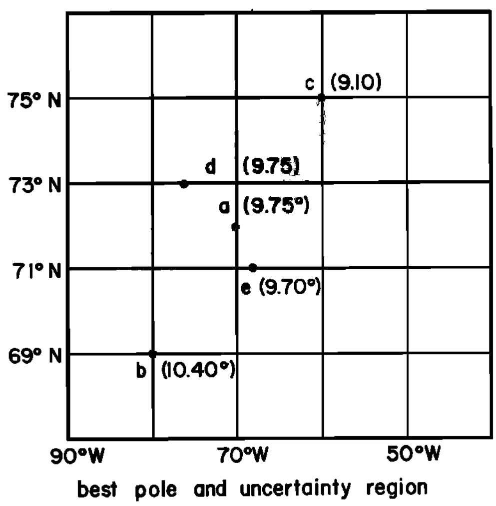

Fig. 6f

Fig. 6. Reconstructions for anomaly 5, South Pacific Ocean. (a) Best fit rotation (b)-(e) End-member rotations. (f) Map showing extent of uncertainty region. Triangles, fracture zone points; circles, magnetic anomaly locations. The Antarctica plate (solid symbols) is held fixed, and the Pacific plate (open symbols) is rotated about the poles indicated in Figure 6f (Table 1).

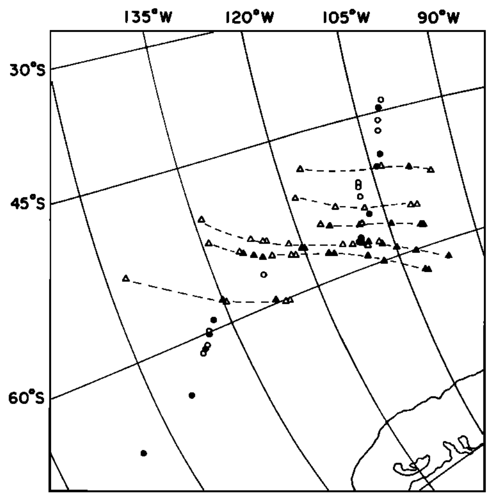

Fig. 7. Best fit reconstruction for anomaly 6, South Pacific Ocean. Symbols are the same as in Figure 6.

began prior to anomaly 33 time, with the separation of the Lord Howe Rise from eastern Australia, and ceased at anomaly 24 time [Hayes and Ringis, 1973]. Consequently, anomaly 24 forms the central northwest-southeast trending anomaly in the Tasman Sea, with older anomalies flanking it on each side. Anomalies 25 through 33 can be clearly identified on east-west magnetic profiles, but there are more data points for anomalies 28 and 32 than the others. So we have made reconstructions for those two times. Poles and angles for the times of anomalies 25 and 31 (Table 2) were obtained by interpolation using best fits for anomaly 28 and anomaly 32 (Figures 13 and 14).

Combined Reconstructions for Anomalies 5, 6, 13, 18: Pacific-Australia

The past relative positions of the Pacific and India-Australia plates can be obtained by com-

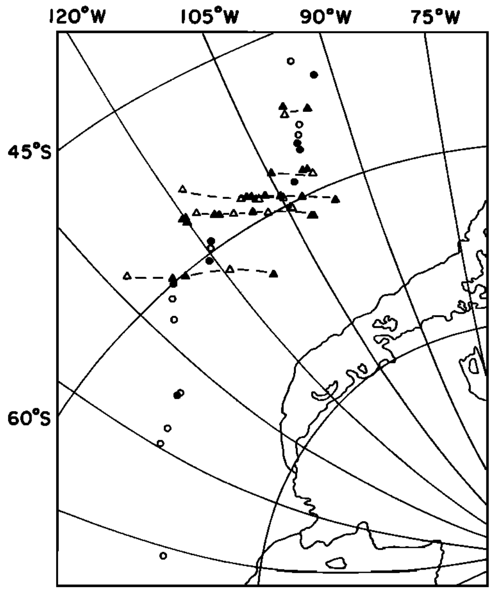

Fig. 8. Best fit reconstruction for anomaly 13, South Pacific Ocean. Symbols are the same as in Figure 6.

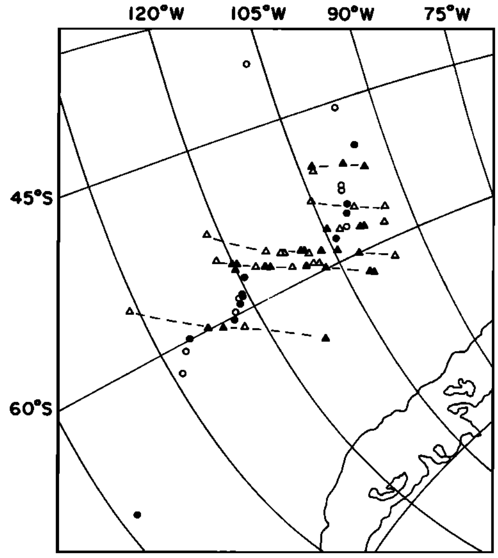

Fig. 9. Best fit reconstruction for anomaly 18, South Pacific Ocean. Symbols are the same as in Figure 6.

bining results from Pacific-Antarctica and Antarctica-Australia spreading, constrained by geologic and geophysical data from the current Pacific-Australia boundary through the Macquarie Ridge, New Zealand, and the Hikurangi-Kermadec trench system. Molnar et al. [1975] calculated past positions of the Pacific plate relative to the India-Australia plate and inferred an Eocene to Recent tectonic history of the Pacific-Australia boundary, which Carter and Norris [1976] showed to be in general accord with the geologic history of the South Island. Ballance [1976] used the geology of the North Island to constrain further the location of the Pacific-Australia plate boundary, still in agreement with the results from the

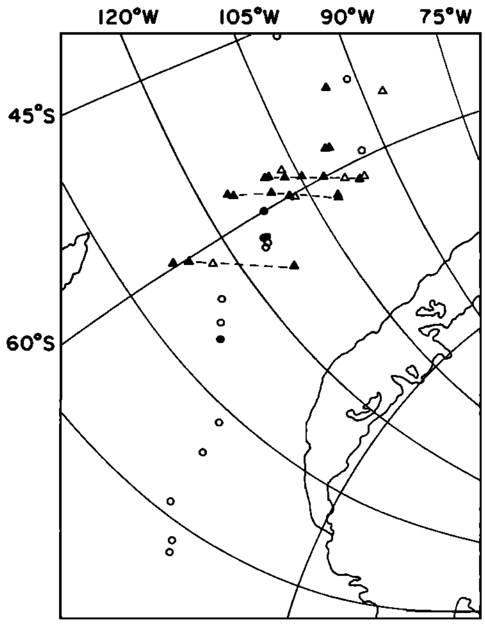

Fig. 10. Best fit reconstruction for anomaly 25, South Pacific Ocean. Symbols are the same as in Figure 6.

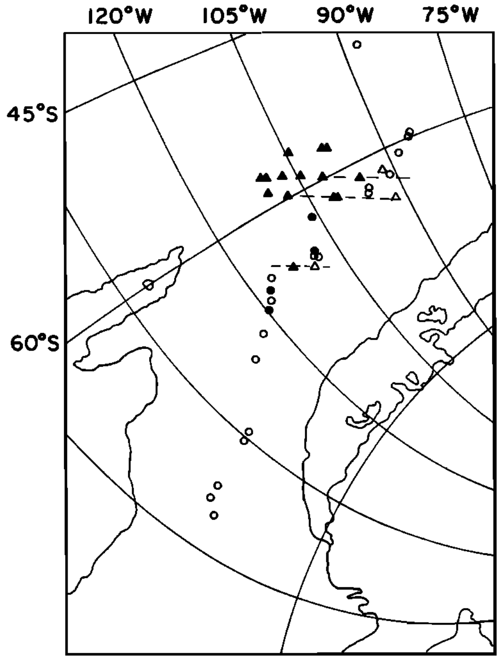

Fig. 11. Best fit reconstruction for anomaly 31, South Pacific Ocean. Symbols are the same as in Figure 6.

marine magnetic reconstructions. In this paper we combined our best fit poles and uncertainty regions for Pacific-Antarctica and Antarctica-Australia relative positions to derive resultant poles and uncertainty regions for Pacific plate-Australia plate relative positions at the times of anomalies 5, 6, 13, and 18 (Figure 15). These differ from previous results [Packham and Terrill, 1975; Walcott, 1978] because they are based on revised, different poles and uncertainty regions for Pacific-Antarctica and Antarctica-Australia spreading.

Our results suggest that the position of the pole for Pacific-Australia finite rotation may not have changed very much from anomaly 18 time (43 m.y.) to anomaly 6 time (19.5 m.y.). The uncertainty regions are large, of the order of 500 km along the long axis and 300 km along the short axis, but for the times of anomalies 6, 13, and 18 they all overlap significantly, so that it is possible that the pole stayed in the same place during this interval.

The revised poles and angles also indicate that the Pacific-Australia finite pole changed some time between the times of anomalies 6 (19.5 m.y.) and 5 (9.8 m.y.). Because our reconstructions only examine the configuration of the system at specific times in the past, this change in the position of the finite pole cannot be dated more precisely. The difference between the locations of the revised anomaly 5 pole and the current best fitting angular velocity vector for the Pacific and India-Australia plates [Chase, 1978; Minster and Jordan, 1978] suggests that the Pacific-Australia finite pole continued to change over the past 9.8 m.y.

Because reconstructions are based on the assumption of rigid lithospheric plates, they should be cautiously applied to the study of deformation within New Zealand itself. The present Australia-Pacific plate boundary through New Zealand is a 200 km-wide zone of distributed dextral shear, faulting, and compression [e.g., Walcott, 1978], which passes northward into subduction of the Pacific plate beneath the North Island at the Hikurangi Trench and southward into subduction of the Australia plate beneath the Fiordland margin of the South Island [Christoffel and van der Linden, 1972]. Seismic activity suggests that a zone 200-300 km wide is currently deforming parallel to the plate boundary through this region [Scholz et al., 1973]. It is not known to what extent bending and dextral shear may have caused the present shapes of the Lord Howe Rise and the Campbell Plateau, but if it is of the same order as the deformation observed in New Zealand, then significant deformation should probably be removed before the plate reconstructions can be quantitatively evaluated. In the figures in this paper, the Lord Howe Rise and Campbell Plateau are divided into two rigid blocks along the Alpine Fault; this is an approximation only, since this is not a rigid boundary and its position and orientation may have changed with time.

A knowledge of the location and orientation of a plate boundary with respect to the instantaneous pole of motion between the two plates allows one to calculate the relative motion along the boundary. This cannot be done very accurately for the past Pacific-Australia plate boundary through New Zealand due to large uncertainties in the reconstructions. Positions of past instantaneous poles from anomaly 18 to anomaly 6 time are very uncertain because the large uncertainty regions of the finite poles overlap. Since the past position and orientation of the Pacific-Australia boundary are also uncertain, a better way to examine the motion between the two plates is to examine the uncertainty in the position of a point on one plate relative to the other plate at specific times in the past. The possible paths traveled by this point through time indicate the expected motion across a plate boundary in that location whatever the orientation of the plate boundary.

The poles and uncertainty regions calculated for Pacific-Antarctica and Antarctica-Australia

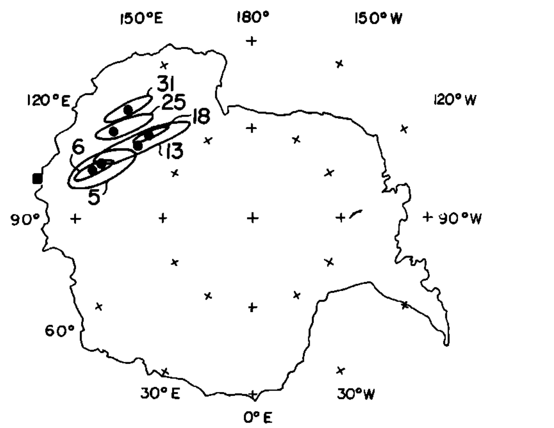

Fig. 12. Orthographic projection showing the location of best fit poles and their uncertainty regions for Pacific-Antarctica relative positions for the times of anomalies 5, 6, 13, 18, 25 and 31. Square, instantaneous pole of Pacific-Antarctica motion [from Minster and Jordan, 1978].

TABLE 2: Other Poles and Angles Used in Reconstructions

Anomaly	Source	Best Pole			End-Members		
		λ	ϕ	θ	λ	ϕ	θ
		Southeast Indian Ocean (Australia-East Antarctica)					
22	2	-8.78	-147.33	24.54			
25	2	-7.27	-146.42	25.14			
31	2	-5.14	-145.15	26.09			
		Pacific Ocean (Pacific-West Antarctica)					
22	1	72.7	-55.81	37.43	71.09	-60.34	35.79
					72.09	-54.34	37.70
					73.09	-58.34	37.00
					75.09	-42.34	41.62
		Tasman Sea					
25	1	-4.49	139.36	-2.12			
31	1	9.48	-40.60	10.08			

Sources: 1, interpolation between recalculated poles (Table 1); 2, interpolation between recalculated pole for anomaly 18, southeast Indian Ocean, and magnetic quiet zone fit of König [1980]. North and east are positive.

positions were used to derive the uncertainties in the past positions of two South Island (Pacific plate) points relative to the Lord Howe Rise (Australia plate) at the times of anomalies 18, 13, 6, and 5. A combination of these results to find the path traveled by these points with respect to a fixed Lord Howe Rise (Figure 16) shows that from anomaly 13 time to the present the best fit positions of these points follow the general trend of the current zone of shear deformation, with ~350 km of displacement from anomaly 13 time to anomaly 6 time, ~90 km between the times of anomalies 6 and 5, and ~330 km of displacement from anomaly 5 time to the present. The uncertainties in the locations of these points at anomaly 6 and anomaly 13 time do not overlap, so that even in the most extreme case, some motion of the Pacific plate with respect to the Australia plate is required. However, a comparison of the anomaly 13 and anomaly 18 positions shows 100% overlap, suggesting that the Pacific and Australia plates could have been fixed with respect to one another during this time. The best fit positions show a small amount of counterclockwise rotation of the Pacific plate with respect to the Australia plate during this interval; such motion is insignificant when compared with later displacements between the two plates and might be difficult to recognize in the geologic record.

The limits on total displacement across the plate boundary (Figure 16) are 820 ± 260 km since anomaly 18 time (43.0 m.y.), 770 ± 330 km since anomaly 13 time (35.6 m.y.), 420 ± 110 km since anomaly 6 time (19.5 m.y.) and 330 ± 110 km since anomaly 5 time (9.8 m.y.). The total displacement across the Alpine and Wairau faults in the South Island is estimated to be 570 km, based on the offset plus the observed horizontal shear of the Permian ultramafic belt and the schist-greywacke boundary [Walcott, 1978]. If all of this deformation is of Cenozoic age, the uncertainties in the plate tectonic reconstructions require that strike-slip deformation along the Alpine-Wairau system began prior to anomaly 6 time (19.5 m.y.). If the shear and strike-slip motion associated with the Alpine-Wairau system represents the total deformation along the Australia-Pacific plate boundary, then this plate boundary was initiated in New Zealand no earlier than the time of anomaly 18 and probably between the times of anomalies 13 (35.6 m.y.) and 6 (19.5 m.y.).

Within the uncertainties, any type of motion might have taken place in the New Zealand region between the Pacific and Australia plates from anomaly 13 time to anomaly 18 time. Geologic evidence from New Zealand shows no major displacement during this interval, although a zone of subsidence, block faulting, and flysch basin formation began suddenly at about the Eo-Oligocene boundary and continued until late Oligocene time [Norris et al., 1978]. This zone of subsidence, the Moonlight Trough, currently trends north-northeast and is offset along the Alpine fault; its original trend may have been modified by subsequent dextral shear, so that its orientation cannot be used to constrain the uncertainties in Pacific-Australia motion. However, the amount of relative motion observed in the geologic record is small enough that the possibility of substantial motion during this interval can probably be eliminated.

Arc volcanics first appeared on the North Island at 24-20 m.y. and extended southward with time, suggesting that the Hikurangi subduction margin east of the North Island formed by southward propagation from the Kermadec Trench [Ballance, 1976]. Our results show 400 ± 370 km of convergence between the Pacific and Australian plates in the interval between anomalies 18 (~43 m.y.) and 6 (~19.5 m.y.). This is consistent with slow subduction taking place for some time before arc volcanism began. Within the uncertainties of the reconstructions, it is possible that the entire Pacific-Australia boundary through New Zealand (consisting of subduction of the Pacific plate under the North Island and right lateral shear across the South Island) developed slowly as a continuous zone of deformation between the times of anomalies 18 and 6.

Combined Reconstructions for Anomalies 18, 22, 25, 31

The time of separation of Australia from Antarctica is a matter of some debate. Magnetic anom-

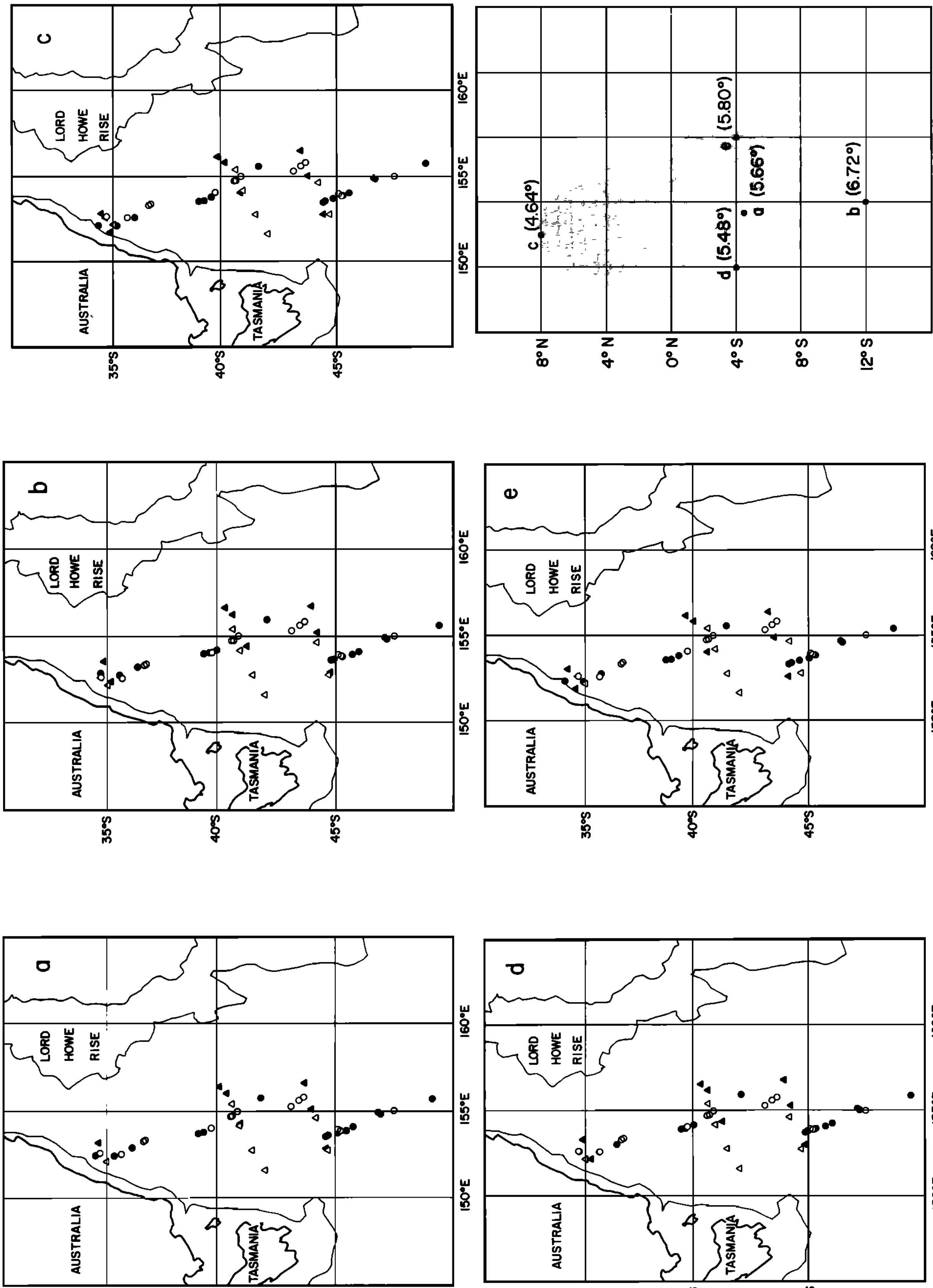

Fig. 13. Reconstructions for anomaly 28, Tasman Sea. (a) Best fit rotation. (b)-(e) End-member rotations. (f) Map showing extent of uncertainty region. Triangles, fracture zone points; circles, magnetic anomaly locations. Australia plate (open symbols) is held fixed, and the Lord Howe plate (solid symbols) is rotated about poles indicated in Figure 13f (Table 1).

alies between anomaly 18 and the older magnetic quiet zones adjacent to the Australia and Antarctica continents were originally identified as anomalies 19 through 22 [Weissel and Hayes, 1972]. Therefore, previous plate reconstructions for this region [e.g., Molnar et al., 1975; Weissel et al., 1977] were based on the assumption that Australia separated from Antarctica shortly before the time of anomaly 22 (53 m.y.), with a nearly constant spreading rate until the present. Recently, Cande and Mutter [1982] reinterpreted these magnetics as anomalies 20 through 34, formed at a very slow spreading rate (~6 mm/yr) after initial separation of Australia from Antarctica between 85 and 110 m.y. ago.

The reconstructions in this paper are based on the revised age of Australia-Antarctica separation, prior to 85 m.y. (See Stock [1981] for a discussion of the uncertainties in reconstructions based on a 53 m.y. age of separation.) Here we assume that the fit of the magnetic quiet zones [Konig, 1980] is appropriate to describe the relative positions of Australia and Antarctica at 85 m.y. This rotation (-28° about 1.5°N, 37°E) is derived from matching the quiet zones along the continental edges, constrained by geologic data, so that the uncertainties in the pole and angle of rotation are difficult to assess and cannot be studied with the techniques used for the reconstructions of magnetic anomalies and fracture zones. Uncertainties in the pole and angle of this rotation are not incorporated into any of the following reconstructions.

Poles and angles for Australia-Antarctica relative positions were obtained by direct interpolation between the magnetic quiet zone rotation and the best fit rotation describing the relative position of Australia with respect to Antarctica at the time of anomaly 18, 43 m.y. (-23.58° about 11.47°N, 31.03°E), assuming a constant spreading rate (Table 2). Because these spreading rates are not well known, no uncertainties have been estimated for these interpolated poles and angles; they are only used to indicate how such early

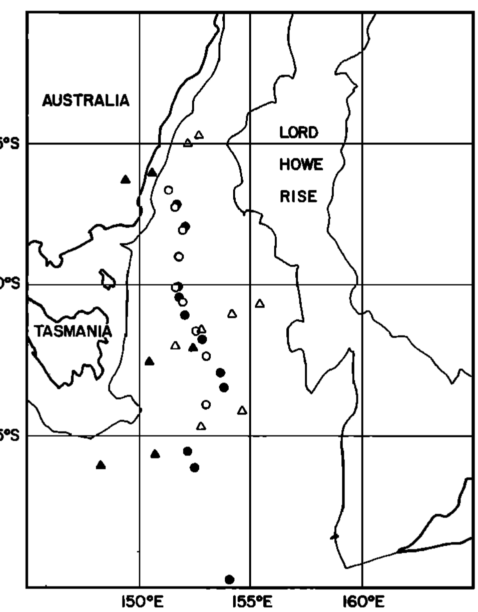

Fig. 14. Best fit reconstruction for anomaly 32, Tasman Sea. Symbols are the same as in Figure 12.

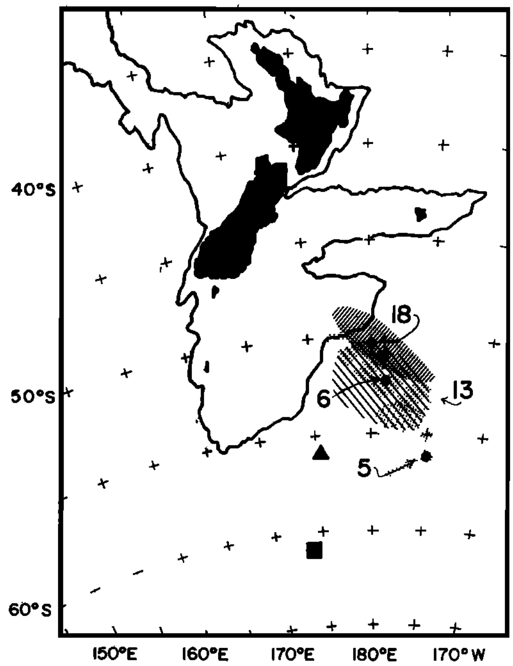

Fig. 15. Orthographic projection of the New Zealand region showing the location of the Pacific-Australia finite poles and the uncertainty regions for the times of anomalies 5, 6, 13, and 18. Also shown are estimates of the location of the present Pacific-Australia instantaneous pole from the best fitting angular velocity vector between the two plates (triangle) and RM2 geohedron (square) [Minster and Jordan, 1978].

separation might have affected the positions of Australia and Antarctica at the times of anomalies 22, 24, and 31. The uncertainties given for point positions at these times (Figures 17 and 18) are based only on uncertainties in reconstructions of the other oceans and would certainly be larger if uncertainties in the Australia-Antarctica poles could be included. Additional uncertainties arise in the location of plate boundaries in this system for times prior to anomaly 18. The southeast Indian Ridge, the Pacific-Antarctic Ridge, and the Tasman Sea spreading center were all active from the time of anomaly 34 to the time of anomaly 24, but spreading in the Tasman Sea stopped at anomaly 24 time. Therefore, from anomaly 24 to anomaly 18 time, only two spreading centers are known to have been active in this system: the Pacific-Antarctic Ridge and the Southeast Indian Ridge. Their spreading rates differ so greatly that they must be due to spreading between two different sets of plates, so that at least one more plate boundary must have existed in the system.

Two logical places to hypothesize the existence of another plate boundary would be (1) between the Pacific and Australia plates or (2) between East and West Antarctica. In previous reconstructions, both these situations have been examined. Molnar et al. [1975] suggested that deformation occurred between East and West Antarctica before Pacific-Australia relative motion began in the mid-Tertiary; Weissel et al. [1977] assumed that since the Late Cretaceous, Antarctica has been a rigid plate but that a plate boundary existed in New Zealand. With Cande and Mutter's [1982] revision

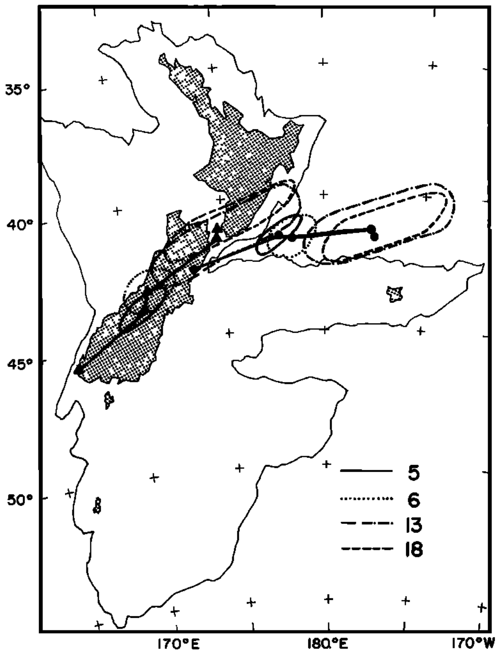

Fig. 16. Orthographic projection showing New Zealand, the positions of two points on the Pacific plate at the present, and best fit positions of these points at the times of anomalies 5, 6, 13, and 18. Oval regions represent the uncertainties in the past positions of these points, derived from uncertainties in marine magnetic reconstructions. The 2-km bathymetric contour of the Lord Howe Rise and the Campbell Plateau is shown for reference.

of the time of separation of Australia from Antarctica, we think that it is worthwhile to reexamine these possibilities, incorporating the uncertainties in the marine magnetic reconstructions. Our reconstructions for times prior to anomaly 18 therefore include two alternative sets of assumptions: first, that Antarctica has remained a rigid plate but that deformation occurred along a plate boundary through New Zealand since Late Cretaceous time, and, second, that the Lord Howe Rise was part of the Pacific plate since the mid-Tertiary but that motion took place between East and West Antarctica prior to the initiation of Pacific-Australia motion.

Constraints on Deformation

New Zealand

The first set of reconstructions for times prior to anomaly 18 assumes that since 85 m.y. there have been four rigid plates in the area: Australia, Antarctica, Pacific, and Lord Howe Rise. Under this assumption of no deformation in Antarctica, there would have been motion along the Pacific-Lord Howe Rise plate boundary since at least 85 m.y. To study the uncertainties in this motion, we combined the poles and uncertainty regions for Pacific-Antarctica and Australia-Lord Howe Rise relative positions (Table 1) with the interpolated poles for Australia-Antarctica relative positions (Table 2) for the times of anomalies 31, 25, and 22. We used these poles to calculate the uncertainties in the past relative positions of two points on the Pacific plate relative to a fixed Lord Howe Rise (Figure 17).

The best fit paths of these points show motion of the Pacific plate in a west-southwest direction relative to fixed Lord Howe Rise between the times of anomalies 31 and 22, followed by motion almost due north until the time of anomaly 18. The amount of motion from the best fit paths is 510 km between anomalies 31 and 25, 100 km between anomalies 25 and 22, and 260 km between anomalies 22 and 18. However, the minimum uncertainty regions given for the positions of these points are large (up to 320 km along the semimajor axis) and would be larger if the uncertainties in the fit of Australia to Antarctica were included. Also, just from the uncertainties already included, there is a 120° range in the possible direction of Pacific-Lord Howe Rise relative motion between the times of anomalies 22 (53 m.y.) and 18 (43 m.y.). Since the uncertainty regions for the locations of the Pacific plate points at the times of anomalies 31, 25, and 18 do not overlap, motion along the Pacific-Lord Howe plate boundary seems required during this interval, but since not all of the uncertainties were included in the calculations, this is not definitive.

In previous plate reconstructions that assumed that Australia and Antarctica separated at about anomaly 22 time, the assumption of a rigid Antarctica plate resulted in a large overlap of the Campbell Plateau and the Lord Howe Rise for the times of anomalies 22 and 25 [Molnar et al., 1975; Weissel et al., 1977]. Using the older age of Australia-Antarctica separation based on Cande and Mutter's [1982] revised magnetics and assuming a constant spreading rate from 85 m.y. until anomaly 18 time, no such overlap results. If the spreading rate were not constant, these recon-

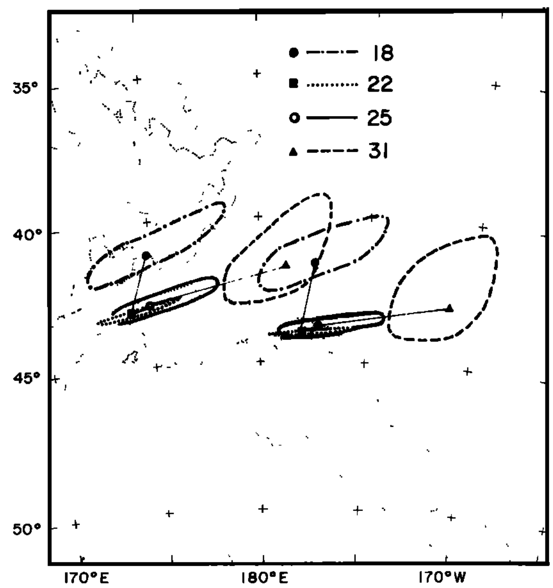

Fig. 17. Orthographic projection showing the positions of two points on the Pacific plate at the times of anomalies 18, 22, 25, and 31 relative to fixed Lord Howe Rise. The best fit position of the Campbell Plateau with respect to fixed Lord Howe Rise at the time of anomaly 22 is also shown. This figure assumes that Australia-Antarctica separation began before 85 m.y.

structions would change slightly but not enough to cause overlap for times previous to anomaly 18.

A regional plate tectonic history based on the assumptions made here therefore indicates west-southwest/east-northeast relative motion between the Pacific and Lord Howe Rise plates from anomaly 31 time to anomaly 22 time and roughly northward convergence from anomaly 22 time to anomaly 18 time. If the past orientation of the Pacific-Lord Howe plate boundary through New Zealand were similar to its orientation today, the motion from anomalies 31 to 22 would have been largely strike-slip. From anomaly 22 to anomaly 18 time, however, the motion would have been a minimum of 140 km of convergence, which exceeds what might be expected based on geologic data from the New Zealand region.

Antarctica

The second set of reconstructions is based on the alternative assumption that the Lord Howe Rise was part of the Pacific plate until some time in the Eocene but that a plate boundary existed between East and West Antarctica from Late Cretaceous to Eocene time. The amount of deformation across this plate boundary would depend on the time when deformation in Antarctica ceased and the time of initiation of the Pacific-Australia plate boundary. We made the simplifying assumption that deformation in Antarctica ceased instantaneously when Pacific-Australia motion commenced. The past positions of two points on West Antarctica relative to fixed East Antarctica are used to show the nature and magnitude of deformation expected across a plate boundary in this region (Figure 18).

If the plate boundary in the New Zealand region developed at anomaly 18 time and a mid-Antarctica plate boundary existed until that time, the best

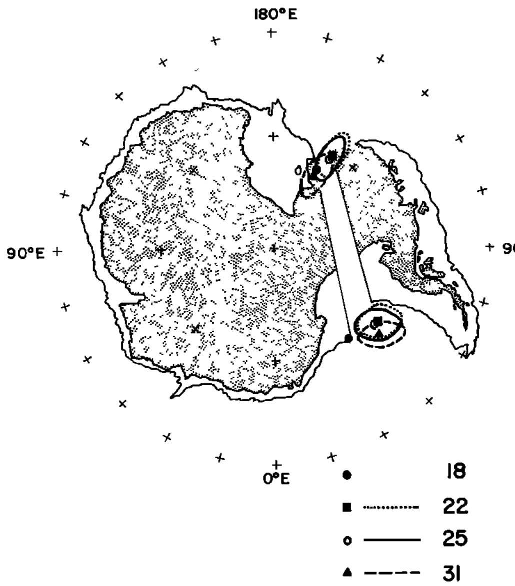

Fig. 18. Uncertainties in the positions of two points on West Antarctica relative to fixed East Antarctica at the times of anomalies 18, 22, 25, and 31, assuming that Australia-Antarctica separation began prior to 85 m.y. The Lord Howe Rise is assumed fixed to the Pacific plate until 43 m.y. (anomaly 18 time).

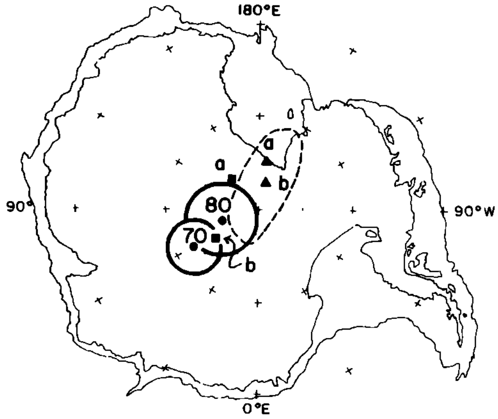

Fig. 19. Position of the Chatham Islands 70-80 m.y. paleomagnetic pole of Grindley et al. [1977] when rotated back to East Antarctica at 68 m.y. (triangles) or 80 m.y. (squares). Alternative assumptions used are (1) no deformation in Antarctica since mid-Cretaceous time, and (2) post middle Cretaceous deformation in Antarctica, with Australia-Antarctica separation before 85 m.y. and the Lord Howe Rise fixed to the Pacific plate prior to anomaly 18 time. The East Antarctica paleomagnetic poles and uncertainty regions from Suárez and Molnar [1979] for 70 and 80 m.y. are shown for comparison. Uncertainties in the rotated positions of the Chatham Islands poles are comparable to the one shown for 70 m.y. pole b.

fit paths of points on West Antarctica (relative to fixed East Antarctica) show clockwise rotation of West Antarctica from anomaly 31 time to anomaly 25 time, 50 km of motion between the times of anomalies 25 and 22, and ~300 km of convergence from anomaly 22 time to anomaly 18 time (Figure 18). The exact motion across the plate boundary would depend on its orientation. The uncertainty regions for the positions of the points are large (semimajor axis ~450 km) and for the times of anomalies 22, 25, and 31 they all overlap, so that it is quite possible that not much motion occurred on this boundary prior to anomaly 22 time. Because of the complex overlap of the uncertainty regions, it is also possible that no motion took place across this boundary between the times of anomalies 22 and 25, but such a situation would violate the assumption that the Pacific-Antarctic Ridge and the Southeast Indian Ridge represent two distinct boundaries at this time.

In this case, we used 43.0 m.y. (anomaly 18 time) as the time of initiation of the Pacific-Australia plate boundary through New Zealand. The oldest recognizable magnetic anomaly due to Pacific-Australia motion is anomaly 18 on the Australia plate west of New Zealand [Weissel et al., 1977], so major Pacific-Australia relative motion must have started at least by this time. Extension in the South Island of New Zealand, however, is not observed until late Eocene-early Oligocene time [Norris et al., 1978]. Either the Pacific-Australia plate boundary passed outside of the New Zealand region prior to anomaly 18 time, or it developed progressively during the Eocene with little motion in the New Zealand region, for instance, with the Pacific-Australia pole close to New Zealand. In any case, there is no evidence for major motion across this boundary prior to anomaly 18 time, so we consider it a reasonable age to use for initiation of the boundary.

Paleomagnetic Constraints

To resolve further the plate history of this region prior to anomaly 18 time, we tested these two situations for compatibility with the apparent polar wander curves of the Pacific and East Antarctica plates. For East Antarctica we used Suárez and Molnar's [1980] pole positions at 70 and 80 m.y. Paleomagnetic measurements from Upper Cretaceous (70–80 m.y.) volcanic rocks from the Chatham Islands give a south pole at 0.45°S, 177.77°W, with an associated circle of confidence of 6.2° [Grindley et al., 1977]. Since the Chatham Islands are east of New Zealand, near the outer edge of the Chatham Rise, their position and orientation with respect to a rigid Pacific plate probably were not affected by Cenozoic shear deformation and bending along the Pacific-Australia plate margin. Therefore, rotation of the Pacific plate back to East Antarctica should bring the Chatham Islands pole into coincidence with the apparent polar wander path of East Antarctica at 70–80 m.y.

We rotated the Chatham Islands pole back to East Antarctica at the times of anomaly 31 (68 m.y.) and anomaly 34 (80 m.y.), using the two previously discussed alternative assumptions for the regional plate history: (1) no deformation in Antarctica and (2) separation of Australia from Antarctica prior to 85 m.y., with the development of the Pacific-Australian plate boundary through New Zealand at anomaly 18 time (Figure 19). Poles and angles used for the 80-m.y. rotations were obtained by direct extrapolation from younger rotations in the South Pacific Ocean and the Tasman Sea and by interpolation between the rotations for anomaly 18 and closure in the southeast Indian Ocean (Table 2).

Neither of these situations gives a best fitting position of the pole for Chatham Rise that is close to the East Antarctica polar wander path at 70 m.y. For 80 m.y., however, the Chatham Islands paleomagnetic pole falls fairly close to the East Antarctica apparent polar wander path in both cases. For both the 70- and 80-m.y. rotations, situation 2 puts Grindley et al.'s pole for the Chatham Islands closer to the East Antarctica pole. However, the uncertainties in the paleomagnetic poles and in the rotations used to compare them combine to give such large uncertainty regions that either case can be considered acceptable.

Both cases predict one direction of motion along the proposed plate boundary between the times of anomalies 31 and 22, with a sharp change in this direction between the times of anomalies 22 and 18. If a plate boundary passed through Antarctica prior to anomaly 18 time (case 25, Figure 18), the motion along the boundary from anomalies 31 to 22 would have been left lateral strike-slip with some separation. This is considerably different from the convergence predicted to occur between anomalies 22 and 18. If instead a plate boundary passed through New Zealand since the late Cretaceous (case 1), the kink in predicted motion between the times of anomalies 22 and 18 would be even more noticeable: relative motion would have followed the same general trend both from anomaly 31 to anomaly 22 and from anomaly 18 to the present but with a 90° change in direction between the times of anomalies 22 and 18 (Figures 16 and 17). This sharp change in predicted direction of motion looks suspicious and may be due to an error in one of the assumptions used to derive the plate configurations for times prior to anomaly 18 (e.g., the assumption that only three plates are active in the system for any given time). Nevertheless, the uncertainties in the past locations of points are large, and it is possible that the change in direction is not as abrupt as the best fit point positions indicate.

Conclusions

Within the limits of their uncertainties, reconstructions of the past relative positions of the Pacific and Australia plates agree well with the amount and timing of deformation observed since the Eocene along the Pacific-Australia plate boundary in New Zealand. In particular, the reconstructions give a history of displacement across this plate boundary of 820 ± 260 km since 43 m.y. ago (anomaly 18), 770 ± 330 km since 35.6 m.y. ago (anomaly 13), 420 ± 110 km since 19.5 m.y. ago (anomaly 6), and 330 ± 110 km since 9.8 m.y. ago (anomaly 5). The best fit reconstructions show little or no motion between about 43 and 35.6 m.y., followed by displacement roughly parallel to the current zone of shear deformation between the Pacific and Australia plates.

If the deformation along the Alpine fault system is all due to relative motion of the Pacific and Australian plates in the Cenozoic, Walcott's (1978) estimate of 570 km of right-lateral faulting and bending on the Alpine system implies that deformation on this fault system began prior to about 19.5 m.y. and probably more recently than 35.6 m.y. These results are consistent with geologic evidence of block faulting, flysch basin formation, and rapid subsidence during the oligocene, all of which may be due to the formation and development of the Australia-Pacific plate boundary. In the vicinity of the North Island, slow subduction may have taken place during the Oligocene, prior to the Late Oligocene-Early Miocene initiation of arc volcanism in the North Island. Results suggest that the instantaneous pole for Pacific-Australia motion may have been fixed from about 43 m.y. to about 19.5 m.y., so that deformation was of similar style throughout this interval. At some time after about 19.5 m.y. this instantaneous pole began to change and has continued to change until the present time. The change of the pole position within the past 20 m.y. may correlate with a change of deformational style along the Pacific-Australia boundary, from strike-slip faulting and dextral shear to compression and associated uplift.

Reconstructions for Late Cretaceous through Eocene time imply substantial motion across a Lord Howe-Pacific plate boundary if the only other boundaries in the system are the Pacific-Antarctica, Antarctica-Australia, and Australia-Lord Howe Rise spreading centers. The quiet sedimentation and lack of tectonic activity in the New Zealand region from the Late Cretaceous through the Late Eocene are inconsistent with this result, suggesting that the assumptions used in deriving the reconstructions are inappropriate.

One way to alter these assumptions is to assume that no plate boundary existed between the Lord Howe and Pacific plates prior to the Eocene but that relative motion took place between East and West Antarctica. In this case, the amount of relative motion that would have occurred between East and West Antarctica depends on the time of separation of Australia from Antarctica and the time of initiation of the Pacific-Australia plate boundary through New Zealand. If Australia separated from Antarctica prior to 85 m.y. ago and the Pacific-Australia plate boundary developed about 43 m.y. ago, not much deformation need have occurred along a mid-Antarctic boundary. We cannot eliminate other possibilities, however.

Based on these assumptions, a reasonable early Cenozoic history of the region appears to be that (1) Australia separated from Antarctica in the Middle to Late Cretaceous [Cande and Mutter, 1982], (2) throughout much of this time there was little motion between the Lord Howe Rise and Campbell Plateau and they may have been parts of the same plate spreading apart from two other plates (West Antarctica and Australia), (3) it is possible that some deformation took place in Antarctica between Late Cretaceous and Late Eocene time, but the exact timing and amount of this deformation is uncertain, (4) the Australia-Pacific plate boundary through New Zealand developed in Late Eocene to Early Oligocene time [Norris et al., 1978].

Acknowledgments. We would like to thank Steve Hellinger, whose computer programs provided the basis for this work, and also Steven Cande for his help and suggestions. This work was supported primarily by the National Science Foundation under grant EAR-7713671. J. M. Stock was partially supported by the M.I.T. Undergraduate Research Opportunities Program.

References

Ballance, P. F., Evolution of the upper Cenozoic magmatic arc and plate boundary in northern New Zealand, Earth Planet. Sci. Lett., 28, 356-370, 1976.

Barron, E. J., and C. G. A. Harrison, Reconstructions of the Campbell Plateau and the Lord Howe Rise, Earth Planet. Sci. Lett., 45, 87-92, 1979.

Cande, S. C., and J. Mutter, A revised interpretation of the oldest sea floor spreading anomalies between Australia and Antarctica, Earth Planet. Sci. Lett., in press, 1982.

Carter, R. M., and R. J. Norris, Cainozoic history of southern New Zealand: An accord between geological observations and plate tectonic predictions, Earth Planet, Sci. Lett., 31, 85-94, 1976.

Chase, C. G., Plate kinematics and the Americas, East Africa, and the rest of the world, Earth Planet. Sci. Lett., 37, 355-368, 1978.

Christoffel, D. A., and W. J. M. van der Linden, Macquarie Ridge-New Zealand alpine fault transition, in Antarctic Oceanology, II, The Australian-New Zealand Sector, Antarctic Res. Ser., Vol. 19, edited by D. E. Hayes, pp. 235-242, AGU, Washington, D.C., 1972.

Gordon, R. G., and A. Cox, Paleomagnetic test of the early Tertiary plate circuit between the Pacific basin plates and the Indian plate, J. Geophys. Res., 85, 6534-6546, 1980.

Grindley, G. W., C. J. D. Adams, J. T. Lumb, and W. A. Walters, Paleomagnetism, K-Ar dating and tectonic interpretation of upper Cretaceous and Cenozoic volcanic rocks of the Chatham Islands, New Zealand, N. Z. J. Geol. Geophys., 20, 425-467, 1977.

Hayes, D. E., and J. Ringis, Sea-floor spreading in the Tasman Sea, Nature, 454-458, 1973.

Hayes, D. E., and J. R. Conolly, Bathymetry of the South Pacific, Antarctic Oceanology, II, The Australian-New Zealand Sector, Antarctic Res. Ser., Vol. 19, edited by D. E. Hayes, AGU, Washington, D.C., 1972.

Hayes, D. E., R. Houtz, M. Talwani, A. B. Watts, J. Weissel, and T. Aitken, Preliminary report of volume 23, USNS Eltanin cruises 33-38, Lamont-Doherty survey of the world ocean, Lamont-Doherty Geol. Observ., Palisades, N.Y., 1975.

Hayes, D. E., R. Houtz, M. Talwani, A. B. Watts, J. Weissel, and T. Aitken, Preliminary report of volume 24, USNS Eltanin cruises 39-45, Lamont-Doherty survey of the world ocean, Lamont-Doherty Geol. Observ., Palisades, N.Y., 1975.

Hayes, D. E., J. Weissel, T. Aitken, R. Houtz, M. Talwani, and A. B. Watts, Preliminary report of volume 25, USNS Eltanin cruises 46-50, Lamont-Doherty survey of the world ocean, Lamont-Doherty Geol. Observ., Palisades, N.Y., 1977.

Hellinger, S. J., The statistics of finite rotations in plate tectonics, Ph.D. thesis, 172 pp., Mass. Inst. of Technol., Cambridge, 1979.

König, M., Geophysical investigations of the northern continental margin of Antarctica, Ph.D. thesis, Columbia Univ., New York, 1980.

LaBrecque, J. J., D. V. Kent, and S. C. Cande, Revised magnetic polarity timescale for late Cretaceous and Cenozoic time, Geology, 5, 330-335, 1977.

Minster, J. B., and T. H. Jordan, Present-day plate motions, J. Geophys. Res., 83, 5331-5351, 1978.

Minster, J. B., T. H. Jordan, P. Molnar, and E. Haines, Numerical modelling of instantaneous plate tectonics, Geophys. J. R. Astron. Soc., 36, 541-576, 1974.

Molnar, P., T. Atwater, J. Mammerickx, and S. M. Smith, Magnetic anomalies, bathymetry, and the tectonic evolution of the South Pacific since the late Cretaceous, Geophys. J. R. Astron. Soc., 40, 383-420, 1975.

Norris, R. J., R. M. Carter, and I. M. Turnbull, Cainozoic sedimentation in basins adjacent to a major continental transform boundary in Southern New Zealand, J. Geol. Soc. London, 135, 191-205, 1978.

Packham, G. H., and A. Terrill, Submarine geology of the South Fiji Basin, Initial Rep. Deep Sea Drill. Proj., 30, 617-646, 1975.

Schlich, R., Structure et age de l'ocean Indien Occidental, Mem. Hors-serie, Soc. géol. de France, No. 6, 1975.

Scholz, C. H., J. M. W. Rynn, R. W. Weed, and C. Frohlich, Detailed seismicity of the Alpine fault zone and Fiordland region, New Zealand, Geol. Soc. Am. Bull., 84, 3297-3316, 1973.

Sclater, J. G., B.P. Luyendyk, and L. Meinke, Magnetic lineations in the southern part of the Central Indian Basin, Geol. Soc. Am. Bull., 87, 371-378, 1976.

Stein, S., and E. A. Okal, Seismicity and tectonics of the ninety-east ridge area: Evidence for

internal deformation of the Indian plate, J. Geophys. Res., 83, 2233-2245, 1978.
Stock, J. M., Uncertainties in the relative positions of the Australia, Antarctica, Lord Howe and Pacific plates since the late Cretaceous, M.S. thesis, Mass. Inst. of Technol., Cambridge, 1981.
Suárez, G., and P. Molnar, Paleomagnetic data and pelagic sediment facies and the motion of the Pacific plate relative to the spin axis since the late Cretaceous, J. Geophys. Res., 85, 5257-5280, 1980.
Walcott, R. I., Present tectonics and late Cenozoic evolution of New Zealand, Geophys. J. R. Astron. Soc., 52, 137-164, 1978.
Weissel, J. K., and D. E. Hayes, Magnetic anomalies in the southeast Indian Ocean, Antarctic Oceanology, II, The Australian-New Zealand Sector, Antarctic Res. Ser., vol. 19, edited by D. E. Hayes, pp. 165-196, AGU, Washington, D. C., 1972.
Weissel, J. K., and D. E. Hayes, Evolution of the Tasman Sea reappraised, Earth Planet. Sci. Lett., 36, 77-84, 1977.
Weissel, J. K., D. E. Hayes, and E. M. Herron, Plate tectonics synthesis: The displacements between Australia, New Zealand, and Antarctica since the late Cretaceous, Mar. Geol., 25, 231-277, 1977.
Weissel, J. K., R. N. Anderson, and C. A. Geller, Deformation of the Indo-Australian plate, Nature, 287, 284-291, 1980.

(Received May 28, 1981;
revised November 10, 1981;
accepted December 11, 1981.)